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# Rapid Generation of Control Charts for Analysis of Complex Gas Mixes in Crisis Situations

I Porter<sup>1</sup> and M Jacobs<sup>1</sup>

## ABSTRACT

After a methane explosion in a coal mine a pre-determined crisis management procedure is instigated. As the process rapidly evolves the inevitable question arises - are personnel trapped underground, are they alive and can they be rescued without putting the lives of the rescue crew at risk? This is a very emotive question with many sub-questions such as; could anybody have survived, is there the potential for a secondary explosion and is there a 'window of opportunity' before that secondary explosion occurs?

To determine if that window of opportunity exists two fundamental elements must be in place; a method of determining the atmosphere at key points in the mine and a method of predicting the course of change of that atmosphere with respect to time. The first element can be achieved if the tube bundle system is intact and drawing samples from known points, alternatively boreholes can be drilled from the surface. The second element can be realised by utilising a sequence of computer generated control charts which have a time axis, a percentage combustibles axis, the upper and lower explosive limits of the current atmosphere and a prediction option which allows the user to look at the potential changes in the atmosphere over a set period of time. These control charts would be part of the mines on-going crisis management system rather than a tool to be used after an explosion had occurred.

## DETERMINING THE EXPLOSIBILITY OF AN ATMOSPHERE

In 1928 H.F. Coward published a paper (Coward,1928) in the Transactions of The Institution of Mining Engineers detailing a method for determining the explosibility of atmospheres behind stoppings. This was the introduction of the Coward's triangle for methane (figure 1), which graphically illustrated the existence of upper and lower limits of percentage methane which when mixed with air will form an explosive atmosphere. Also illustrated was how the upper and lower (marginally for lower) combustible gas percentage varies with percentage oxygen. By plotting a particular mix of methane and oxygen on the diagram it can be determined if that atmosphere is either explosive, explosive with the addition of methane, explosive with the addition of fresh air or cannot become explosive.

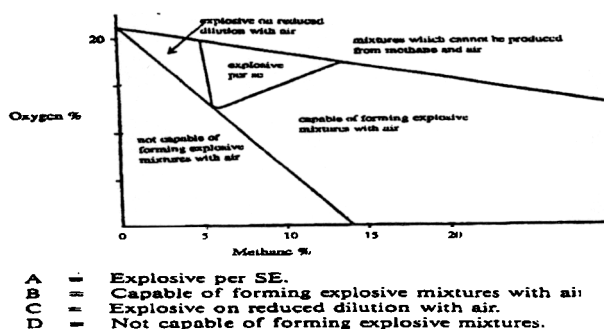


Fig. 1 - Coward's triangle for methane

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The basic Coward's diagram can be expanded to take account of the explosive potential of other gases such as CO and H<sub>2</sub>, however, there are still a number of limitations regarding analysis during an emergency situation. The primary limitation is the difficulty in following the trend of the mix with respect to time particularly when the ratio of the various combustibles varies, hence changing the shape of the triangle. A number of solutions to these limitations have been proposed. Hughes and Raybould (1960) developed the idea of control charts which had time as the x-axis and percentage combustibles on the y-axis. For a given mixture (sampled at a known time) the upper and lower critical values can be determined from the explosive triangle and these can be plotted on the control chart against time. The state of the atmosphere is also plotted on the chart. A new triangle is developed for each new sample and the control chart is modified accordingly. After a number of samples have been analysed a trend can be established (figure 2). The problem with this is the time taken to develop the new triangle and update the control chart in a crisis situation.

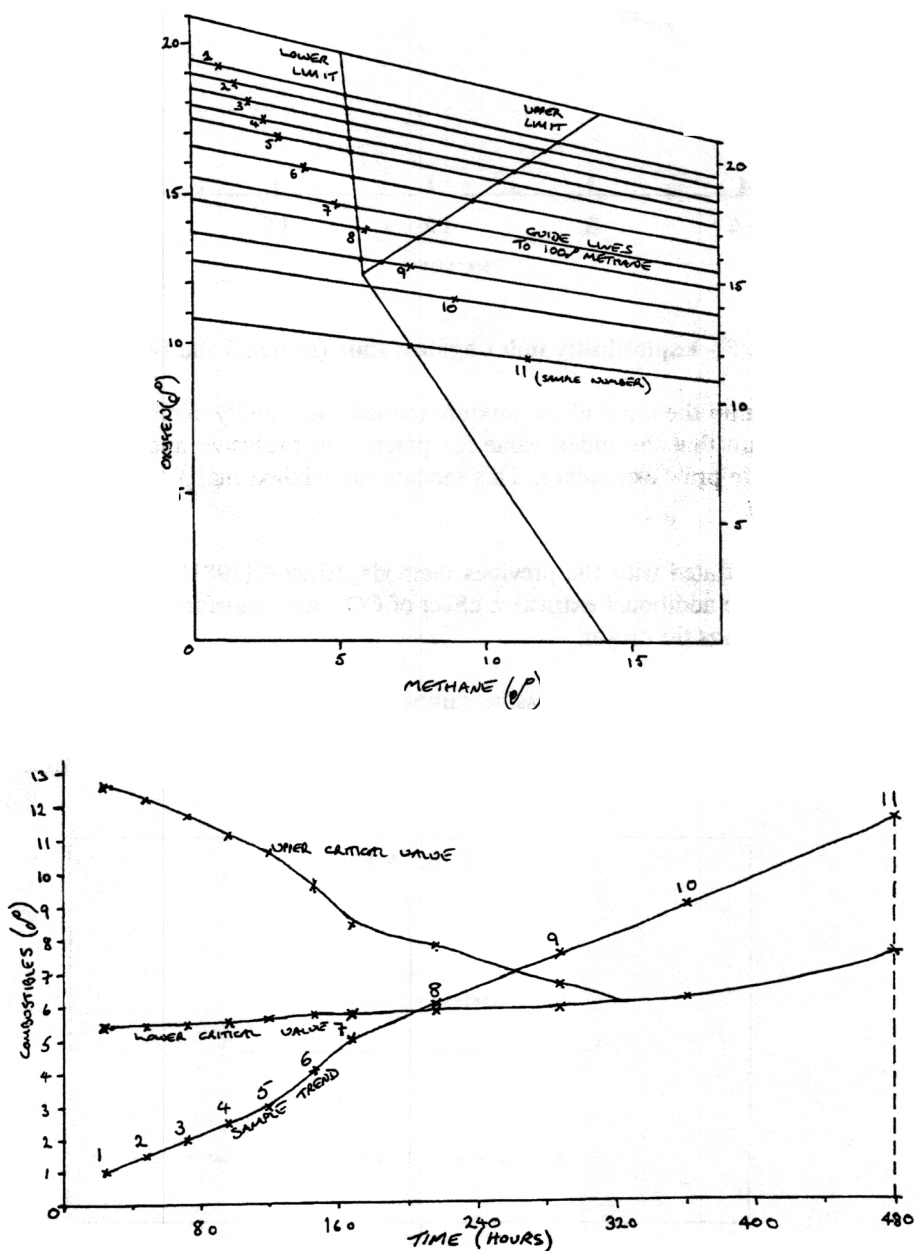


Fig. 2 – Manually developed control chart illustrating method of construction

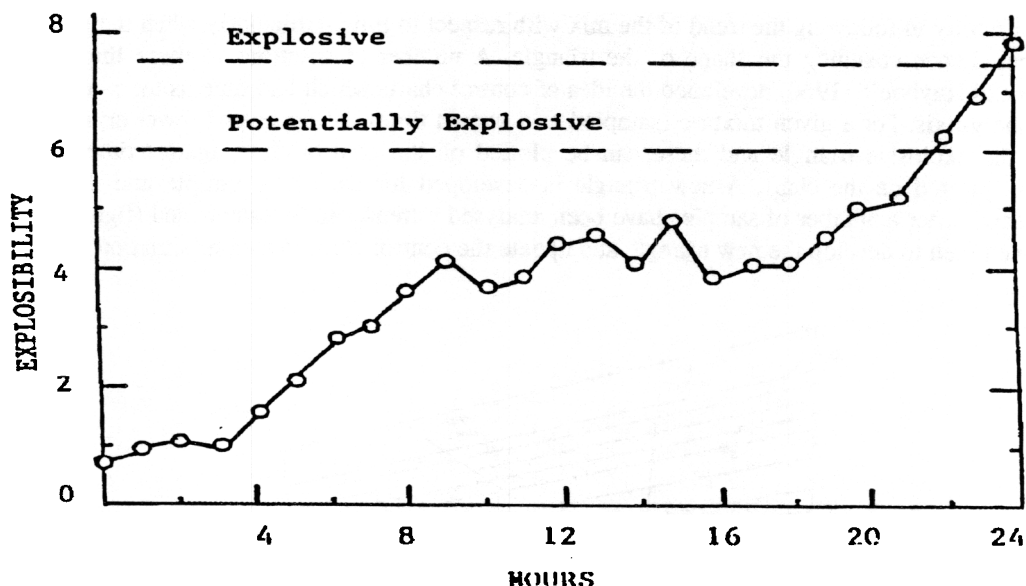


Fig. 3 - Explosibility index against time (Mitchell and Burns, 1979)

As can be seen from the diagram the trend of the mixture towards potentially explosive and explosive can be visualised. Limitations of this method are that the index value for potentially explosive and explosive situations can vary from location to location and require prior experience. This renders the method inappropriate for crisis situations where time for evaluation is at a premium.

To alleviate the problems associated with the previous methods, Ellicott (1981) modified the flammability triangle for complex mixes by including the additional extinctive effect of  $\text{CO}_2$  and transforming the triangular diagram into an x-y plot (Fig. 4) with the nose point as the origin.

From the diagram it can be seen that as successive samples are plotted the trend of the atmosphere can be rapidly established. As with the original flammability triangles the limitation of the diagram is the lack of a time scale, hence requiring additional time consuming calculations to determine the trend of the sample with time.

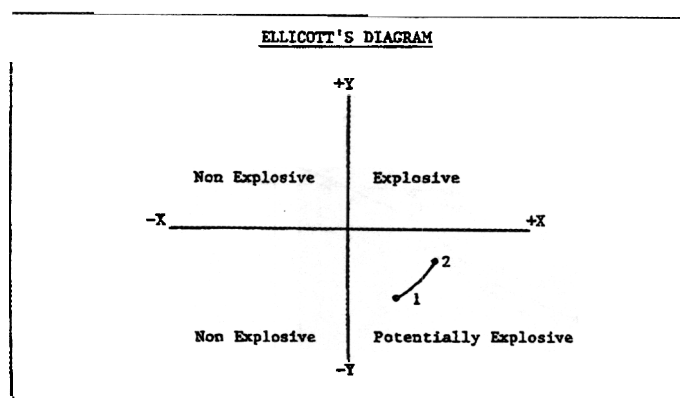


Fig. 4 - Ellicott's diagram (Ellicott, 1981)

## COMPUTER GENERATED CONTROL CHARTS

To overcome all of the aforementioned limitations a computer program (EXGAS) was developed to automatically generate control charts which show a plot of combustibles against time. Also included on the plot are the upper and lower critical limits of the flammability triangle for that particular mix of flammables. Fig. 5 is an example of a control chart generated by the program.

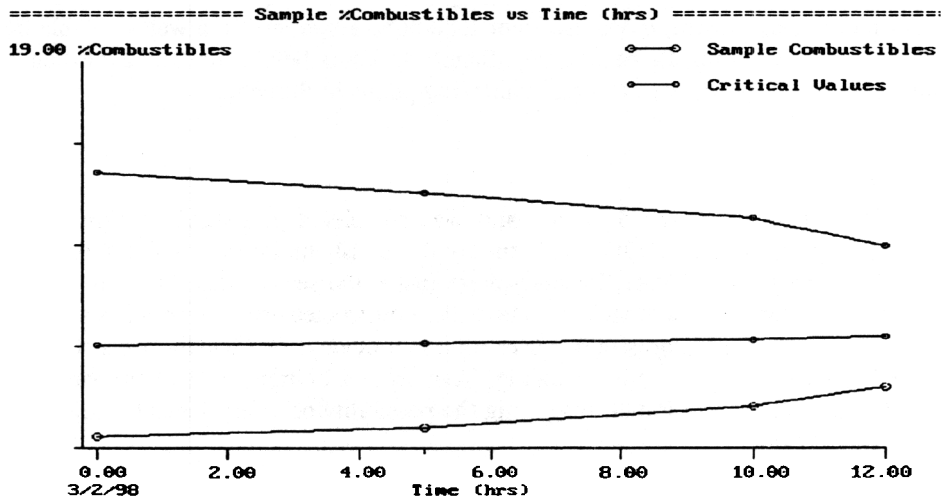


Fig.5 - Computer generated control chart

Included in the algorithms used to generate the control charts are the greater extinctive effect of CO<sub>2</sub> over nitrogen and the effect of temperature on the shape of the flammability triangle for methane. If the greater extinctive effect of CO<sub>2</sub> were not included any errors so resulting will be on the safe side, however, table 1 shows that omitting the effect of temperature does not err on the safe side, particularly in a fire situation.

Table 1 - Effect of Temperature on Flammability Limits (Weimann,1983)

Temperature (°C)	Lower Limit (CH <sub>4</sub> %)	Upper Limit (CH <sub>4</sub> %)	Nose Point (O <sub>2</sub> %)
20	5	14	12.2
250	4	18.5	9.5
500	3	20	7.2 <sup>#</sup>

# extrapolated approximation

After two data points are entered the program can then be set to prediction mode. The prediction mode can predict the trend of the given atmosphere and can also predict the future shape (upper, lower and nose) of the explosive triangle taking into account the various factors which effect the explosibility limits. Also, as the data points for the program are taken from the gas analysis system it was a simple matter to add an algorithm to determine the CO/O<sub>2</sub> deficiency ratio (Graham's Ratio) which would indicate the likelihood of a spontaneous combustion situation occurring; ie. a potential source of ignition. This could also be added to the prediction mode. A significant potential of the programme is that with some minor software modifications and appropriate interfacing, the system can be connected directly to the gas analysis system and run in the background of any networked computer. If an event were unfolding and is detected automatically (say using an automated 24 hour prediction mode) it would generate a warning message which overrides the screen output and audio output of particular systems such as the main control. This system could not be overridden without certain actions being undertaken.

## APPLICATION OF PROGRAM TO KNOWN DATA

The following data is taken from reports (Simtars 1995,) relating to the explosion in the area of 512 Panel at Moura No 2 Underground coal mine on 7 August 1994. As the only information taken into account is that from the gas monitoring system, the analysis does not profess to judge, draw conclusions on, or attribute blame to any person or operation associated with the explosion and post explosion events. It merely illustrates some of the potential advantages associated with the rapid production and analysis of control charts using the EXGAS program. The data analysed was obtained from the records of the gas monitoring system, a Maihak Unor tube bundle system. Data was available from 27 July, but was analysed only from 6 August when results became significant, 48 hours before the first explosion occurred. Fig. 6 is a plan of the workings around 512 Panel, with the gas monitoring points highlighted.

### Sealing 512 panel

Work to seal 512 Panel started on Friday 5 August and was completed at around 1:15am on Sunday 7 August. In preparation for final sealing, at around 2:30pm on Saturday 6 August, monitoring point 5 was relocated to 20 metres inside the seal in No 3 heading, to monitor the atmosphere inside the sealed area. Point 16 was moved at 2:00am on Sunday 7 August to south return of 510 Panel. Tectrete seals, constructed of wire mesh baskets into which plaster is poured, were utilised. The plaster builds up strength over time to provide a seal which meets statutory requirements. The position of these seals is shown in Fig. 6. Prior to sealing, from around 17 June 1994, there had been several reports of a benzene or tarry smell in the area of 512 Panel, suggesting the possibility of spontaneous heating. The source of the smell proved elusive (SIMTARS, 1995).

### Analysis of data from monitoring point 5

As stated previously data was available for all points from 27 July 1994, but prior to the explosion only monitoring point 5 provided significant data. This point, originally located in the north west return of 512 Panel, indicated relatively stable levels of CH<sub>4</sub> and CO until around 9:00 am on 6 August. After this time the methane level increased from around 0.30% to 0.85% at 2:30 pm on the same day, at which point it was transferred to its post sealing location 20 metres inbye the seal position of No 3 heading. Initial readings from this position were between 0.20% and 0.30% methane. Carbon monoxide levels at this time did not exceed 3 ppm and this was the case up to 4 hours before the final sealing. The CO level then increased steadily to over 10 ppm (a CO/O<sub>2</sub> deficiency ratio of 0.2) about an hour before sealing and continued to climb after sealing to reach 102 ppm (a CO/O<sub>2</sub> deficiency ratio of 0.66) at 2:57 pm on 7 August. It should be noted that sealing an area does not in itself produce an oxygen deficient atmosphere, it is the oxidation of the carbonaceous material within the sealed area that does so. The combustible content of the atmosphere at 2:57 pm was 3.4%. At this point, using the prediction option from EXGAS, the time to the lower limit was around 9.5 hours (12 midnight). By 6 pm that evening the deficiency ratio had risen to 0.7 and the methane level had reached 4%, and with an oxygen level of 18.7% the atmosphere was rapidly approaching the lower explosive limit. The prediction function indicates that the time to the lower limit was 5.5 hrs (11:30 pm). Depending on which particular sample is analysed, the time at which the atmosphere reaches the lower limit varies from 11 pm to midnight. This variance is not critical, at this stage, as a time range rather than an exactness is required. As the background level for the deficiency ratio was between 0.1 and 0.2 and had risen to 0.7 it suggests that there may be heating (source of ignition) in the vicinity of a potentially explosive atmosphere. At this point a warning message would be generated by EXGAS and a potential crisis situation indicated.

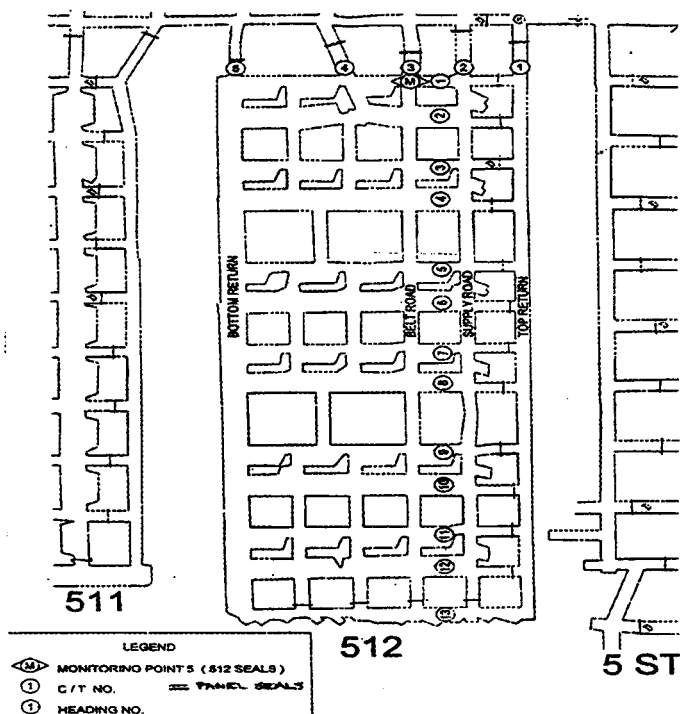


Fig. 6 - Gas monitoring points and seals in the vicinity of 512 panel (SIMTARS, 1995)

Continuing to use EXGAS to produce control charts and predict the future state of the atmosphere would show the following situation, Fig. 7, at 10 pm, one hour and forty minutes before the explosion.

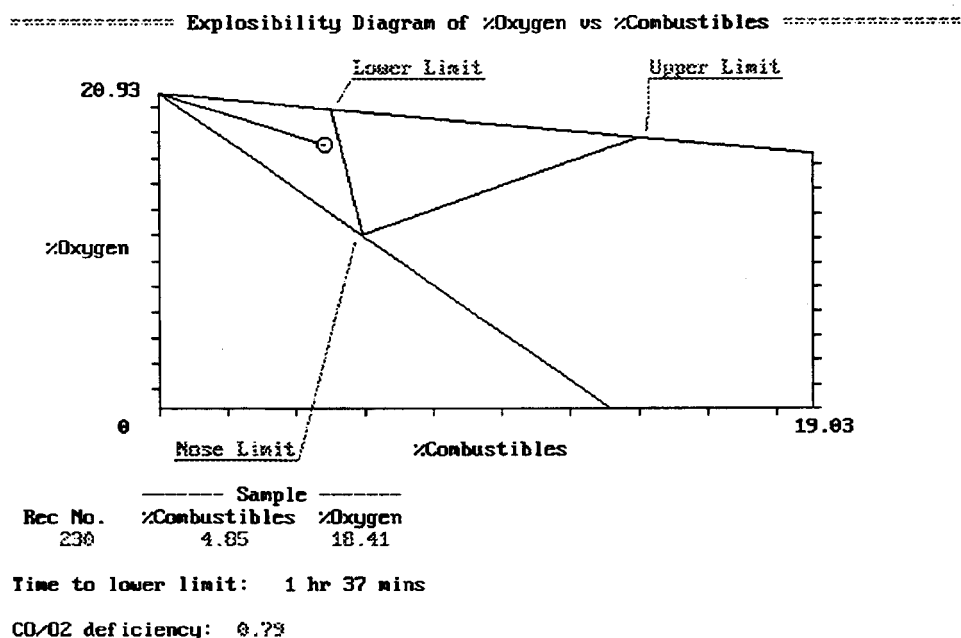


Fig. 7 - Output from EXGAS for data recorded at 10 pm, 7 August.

This shows that the deficiency ratio has risen to 0.79 and that the atmosphere will reach the explosive limit at 11:37 pm. Other samples taken around this time show similar deficiency ratios and a lower limit time of plus or minus a few minutes off 11:35 pm. Continuing to view the crisis, at 11:08 pm the deficiency ratio had risen to 0.82 and the lower limit was predicted for 11:40 pm. If all these factors could have been rapidly put together at the mine, there was still 30 minutes to get the miners in the vicinity of 512 Panel to relative safety. Fig. 8 shows the control chart for the 72 hours up to and after the incident.

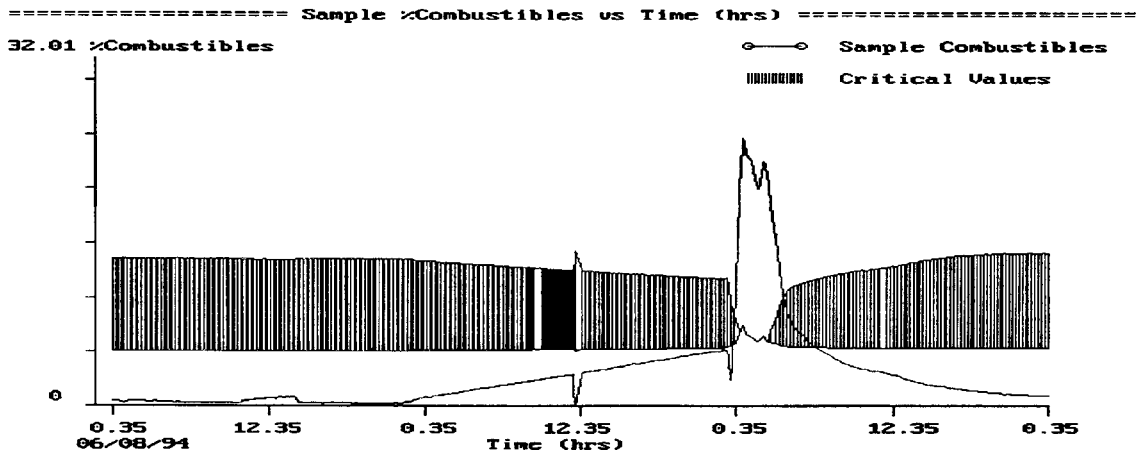


Fig. 8 - Seventy two hour control chart from 6 August to 9 August 1994

### DISCUSSION

It's easy to be wise in hindsight. The above analysis of data from gas monitoring point five, indicates that all the information required to advise the removal of all personnel from the area before the explosion was available. At the mine the information from analysis of the gas data, although used to predict the time the atmosphere would reach the lower limit, did not, for whatever reason, appear to warn of the potential source of ignition. To warn of the impending crisis, output from the gas analysis system would have to be viewed and analysed by a skilled person who had knowledge of the indicators of spontaneous combustion. That person would have to have been on-site that day (a Sunday) and have been available to monitor the trend in the atmosphere. In the current corporate climate of economies of scale in personnel and multi-tasking this is too great a risk to leave to chance. It would therefore be desirable to have access to a program such as EXGAS with the facility to take output directly from the gas analyser and have this linked to a crisis management program (currently under development at the University of Wollongong) which would give an audible and visual alarm if a crisis situation was predicted. The crisis management program would then provide a step by step procedure that any mine personnel could follow.

An important point to note is that monitoring point 5 is the only sampling point in the sealed area. Is the atmosphere sampled at this point indicative of the atmosphere in the rest of the area and is it acceptable to use these values in a crisis situation? The answer to both these questions is open to conjecture, but probably to the negative. It would be correct to say that a number of points situated at key locations would be desirable. Determining the optimum number and location of monitoring points should be the subject of future research.

### CONCLUSION

As only methane is taken into consideration in the case study the full potential of the control charts may not be obvious. In fact analysis of the explosibility data could have been, and in fact was prior to the first explosion, done manually. If, however, temperature and other combustible gas variations were taken into account, manual calculation of the control charts and prediction of trends with respect to time would be laborious and overly time consuming. The program at it's current stage of development goes some way to solving this problem.



So where was that window of opportunity - the 36 hours between the first and second explosions? Unlikely, as analysis by gas chromatograph of samples taken from boreholes drilled into 512 panel after the first explosion showed that methane levels were high and the potential for a second explosion existed during the full 36 hours.

The window of opportunity did in fact exist in the 12 hours before the first explosion. If surface personnel had access to appropriate computer hardware and software, the crisis situation which was unfolding may not have been missed and evacuation of underground personnel could have taken place.

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